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THE EPA COMPLEX TERRAIN MODEL: THEORETICAL BASIS AND PRELIMINARY EVALUATION

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ABSTRACT

The theoretical basis, physical structure, and preliminary evaluation of the U.S. Environmental Protection Agency's Complex Terrain Dispersion Model (CTDM) are described. CTDM is a point-source plume model designed primarily to estimate windward-side surface concentrations on distinct terrain features during stably-stratified flow. The model is based on steady-state, Gaussian diffusion assumptions. Potential flow theory is the basis of the model mechanisms for accounting for terrain-induced alterations in the flow. The model incorporates the critical dividing streamline height concept to separate the flow capable of surmounting the terrain from that restrained to flow around the terrain. Consideration is given to plume meander, source-induced effects on initial diffusion, and alterations in diffusion rates by flow deformation. Preliminary evaluations of the the current version of the model with field tracer data and fluid modeling data show that CTDM can identify maximum concentrations with some success but that further refinements are warranted.

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INTRODUCTION

As a major focus of its ongoing Complex Terrain Model Development program, the U.S. Environmental Protection Agency is developing a point-source plume model for simulating dispersion over irregular terrain during stably stratified flow. The current version of the Complex Terrain Dispersion Model (CTDM) is designed primarily to estimate windward-side surface concentrations on distinct terrain features during plume impingement conditions. CTDM retains much of the simplicity of steady-state, Gaussian diffusion models while incorporating many theoretically- and empirically-derived concepts about stratified flow and diffusion over complex terrain.

Terrain-induced flow alterations in CTDM are based on potential flow theory around two- and three-dimensional elliptical terrain features. The model addresses specifically the effects on diffusion rates caused by these flow alterations.

The primary purpose of this paper is to present a qualitative description of CTDM and report on some of the comparisons of model calculations with data from field tracer studies and fluid modeling simulations. A detailed description of the model and its performance is contained in Strimaitis et al. (1985), DiCristofaro et al. (1986), and Strimaitis et al. (1986)

MODEL STRUCTURE AND THEORETICAL BASIS

A basic feature of CTDM is the use of the critical dividing streamline height (H_c) which distinguishes the flow (above H_c) with enough kinetic energy to surmount the terrain from the flow (below H_c) restricted to move primarily in a horizontal plane. This concept was suggested by Sheppard (1956) and Drazin (1961) and demonstrated experimentally by Riley et al. (1976), Brighton (1978), Hunt and Snyder (1980), and Snyder and Hunt (1984). H_c can be computed from

profiles of wind speed and temperature by equating the kinetic energy of the flow with the potential energy obtained by raising a parcel from H_c to the top of the terrain feature (hill). The integral formula used is

$$\frac{1}{2} U^2 = \int_{Hc}^{h} \frac{g}{\Theta} \left[\frac{\partial \Theta}{\partial z}\right]\left[h-z\right] \, dz \qquad (1)$$

where U is the wind speed at H_c, h is the hill height, g is the acceleration due to gravity, and Θ is the potential temperature. Eq. 1 is solved iteratively.

The model separately computes the contribution from the pollutant in each of the distinct flow regions to the hill surface concentration at a given receptor. As shown in Fig. 1, the plume develops in a flat terrain mode until it reaches the hill. Afterwards, the LIFT routine in CTDM deals with the part of the plume above H_c and the WRAP routine deals with that below H_c. To simplify the modeling, H_c is assumed to be a level surface.

Flow above H_c (LIFT)

The flow above H_c is taken to be weakly stratified such that stratification influences the flow without significantly inhibiting vertical motion. The flow above H_c is also assumed to be influenced only by that portion of the hill above H_c.

Modifications to the pollutant plume arise from distortion in the flow. A flow streamline in the LIFT domain will be deflected to one side or the other of the crest and its height above the surface will be reduced. Adjacent streamlines are generally displaced by differing amounts resulting in changes in streamline spacing and associated changes in local speed. The plume distorts such that it is thinner in the vertical and wider in the lateral, the actual plume trajectory is curved, and the travel time of a parcel in the plume varies nonlinearly with

diffusion is enhanced by the contraction of streamlines in the vertical direction and retarded by expansion of streamlines in the horizontal direction.

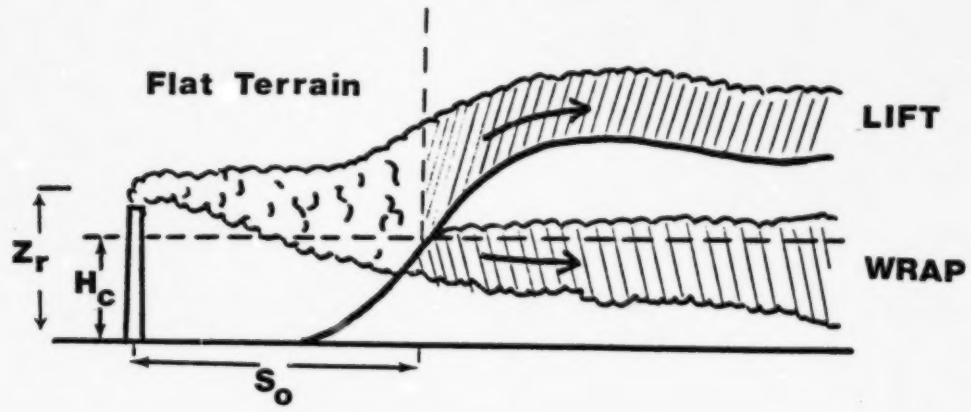

Fig. 1. Idealized stratified flow about a three-dimensional hill where the domains of the CTDM algorithms are indicated. The distance, s_o, is from the source to the intersection of H_c (dividing streamline height) with the hill.

In LIFT, the plume is allowed to develop as if in flat terrain until the point where H_c intersects the terrain. The distance from the source to this intersection point is s_o. If H_c is zero, s_o is the distance from the source to the windward base of the hill. Beyond s_o, the plume material below H_c is disregarded by LIFT, and the material above H_c is modeled as if the terrain is flat and H_c is the lower boundary. Alterations in the flow and plume are accounted for with terrain factors. Specifically, the wind speed, plume height above H_c, plume spread, and lateral position of the plume center are modified to reflect the average terrain-induced plume changes between s_o and s (where s is the source to receptor distance).

The LIFT routine takes the flat-terrain Gaussian distribution of plume material at s_o and re-initializes it into an array of point sources each representing an elemental flux of pollutant through the y-z plane at $x=s_o$. Note

that the x-axis lies along the flow direction, the y-axis is crosswind, and z-axis is vertical. The source strength, dQ, at each of these point sources is given by

$$dQ(s_o,y,z) = C(s_o,y,z)u\ dy\ dz$$

where $C(s_o,y,z,)$ is the concentration at a particular point source in the array and U is the mean wind speed. The concentration at any receptor downwind of s_o is the integrated (summed) impact from all of these elemental sources. LIFT uses average values (over the distance from s_o to the receptor at s) of changes in the flow properties to adjust the concentration distribution (point source array) at s_o. Fig. 2 provides a simplified description of how the model treats the plume in the vertical.

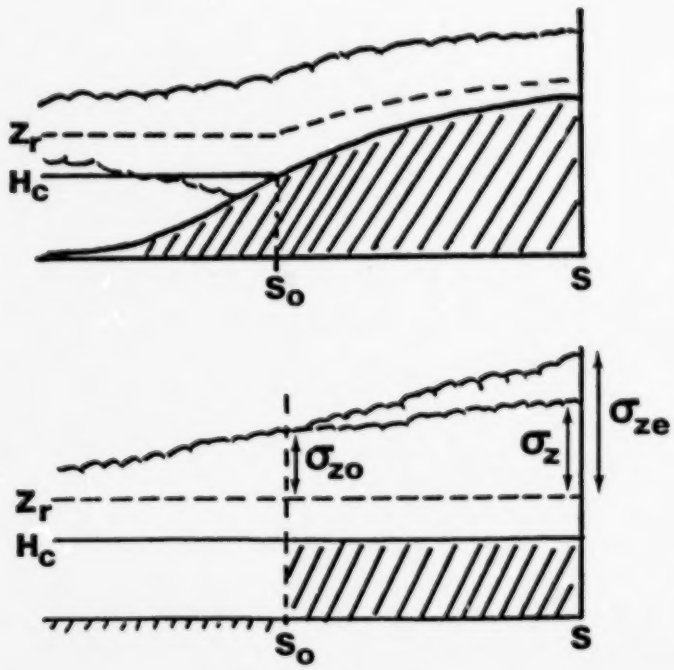

Fig. 2. Illustration of the model treatment of the vertical distribution of plume material above the critical dividing streamline height (H_c). z_r is the release height, σ_{zo} is the vertical plume size at s_o, σ_{ze} is the effective vertical plume size at s (the receptor) discussed later, and σ_z is the vertical plume size at s if no terrain had been present.

In essence, LIFT distorts the plume at s_o and a flat terrain computation is used to estimate the effects of these distortions on the diffusion of the material to the surface over the interval $s-s_o$. In this way, a continuous process is represented by a two-step process in which distortion and diffusion are treated successively. In addition, the simplicity of the flat terrain Gaussian plume solution is retained with terrain effects explicitly incorporated.

Quantities in the distorted flow, beyond s_o, are related to quantities in the undisturbed flow by terrain factors. These factors depend on the position of the receptor since they are a measure of the average effect on the flow and diffusion from s_o to s. T_h and T_l are factors that specify the amount of streamline distortion in the vertical and lateral directions respectively; T_u specifies the resultant changes in flow speed; and $T\sigma_z$ and $T\sigma_y$ specify changes in the diffusivity in the vertical and lateral directions.

The factor T_h accounts for the effective contraction or expansion of the vertical distance between streamlines. Even though streamline spacing is actually a function of height, this factor is considered a constant over all streamlines and therefore is applied at plume centerline height. Similarly, T_l and T_u are constant for a particular plume path. To conserve mass, the condition $T_h T_l T_u = 1$ is maintained at every point in the flow. The magnitudes of all the terrain factors are scaled from potential flow calculations. These computations have been performed external to CTDM for flow over the crest of an ellipsoid (Lamb, 1945) for selected combinations of alongwind and crosswind aspect ratios. Away from the crest, the flow modification diminishes and the terrain factors are relaxed to unity. In this way, the terrain effects can be incorporated by a limited number of parameters and thus determined analytically. This avoids the need for extensive potential flow computation and numerical integration within the CTDM code.

In summary, above H_c, the flow is re-initialized at s_o, the plume distribution and the distance between plume center and H_c are adjusted by an amount representative of the average distortion from s_o to s, and this distorted distribution is allowed to disperse as an array of point sources over flat terrain with adjusted diffusion rates. The concentration at a receptor is the integrated contribution from these point sources.

The resulting equation for the concentration at a receptor on the hill surface at (s,y_R) for an original source location at $(0,y_r,z_r)$ is given by

$$C(s,y_R,0;s_o) = \frac{Qe^{-0.5\left(\frac{y_R/T_l - y_r}{\sigma_{ye}}\right)^2}}{2\pi\sigma_{ye}\sigma_{ze}u} \left[e^{-0.5\left(\frac{z_r-H_c}{\sigma_{ze}}\right)^2}\left(1-\mathrm{erf}\left(\frac{H_c-z_r}{\sqrt{2}\sigma_{ze}}\,\frac{\sigma_z^*/T_z}{\sigma_{zo}}\right)\right)\right.$$

$$\left. + e^{-0.5\left(\frac{z_r+H_c}{\sigma_{ze}}\right)^2}\left(1-\mathrm{erf}\left(\frac{H_c+z_r}{\sqrt{2}\sigma_{ze}}\,\frac{\sigma_z^*/T_z}{\sigma_{zo}}\right)\right)\right] \qquad (2)$$

where erf is the error function, $T_z=T_h/T\sigma_z$, $T_y=T_l/T\sigma_y$ and Q is the source strength. The effective plume size is given by

$$\sigma_{ze}^2 = \sigma_{zo}^2 + \sigma_z^{*2}/T_z^2$$

$$\sigma_{ye}^2 = \sigma_{yo}^2 + \sigma_y^{*2}/T_y^2$$

where $\sigma_y^{*2} = \sigma_y^2 - \sigma_{yo}^2$ $\qquad$ $\sigma_z^{*2} = \sigma_z^2 - \sigma_{zo}^2$

The terrain-induced modifications in Eq. 2 are much easier to observe if H_c is set to zero (entire plume is handled by LIFT). Eq. 2 becomes

$$C(s,y_R,0;s_o) = \frac{Qe^{-0.5\left(\frac{y_R/T_l - y_r}{\sigma_{ye}}\right)^2}}{\pi\sigma_{ye}\sigma_{ze}u} e^{-0.5\,(z_r/\sigma_{ze})^2} \qquad (3)$$

Eq. 3 differs from the flat-terrain Gaussian equation in the effective plume

spread parameters (σ_{ye},σ_{ze}) and the apparent lateral shift in the receptor (y_R/T_e). If the terrain is removed, the terrain factors revert back to unity and $y_R/T_1=y_R$, $\sigma_{ye}=\sigma_y$, $\sigma_{ye}=\sigma_z$ and the flat terrain equation is returned.

Examining Eq. 3 further, if T_1 is greater than 1, which is generally the case because the streamlines are deflected to the side to some degree, the apparent receptor location (y_R/T_1) lies nearer to the plume centerline. When T_z is less than 1, which is generally the case, σ_{ze} exceeds σ_z at s and more plume material may lie nearer to the surface. Also, T_y is generally greater than one and σ_{ye} is less than σ_y at s, so the plume is less dilute laterally. As a consequence, Eq. 2 may estimate hillside surface concentrations in excess of flat terrain concentrations even when H_c is zero. If H_c is nonzero, but below plume centerline, Eq. 3 will estimate even greater hill-surface concentrations because the portion of the plume below H_c is removed allowing less dilute material to approach nearer the surface. If $H_c=z_r$, then the centerline is placed at surface level (Fig. 2) producing the "impingement" result.

The LIFT routine also accounts for horizontal meander during the averaging period. A filament (or narrow) plume is defined for a period commensurate with the travel time from source to terrain and the concentration over the total averaging period is a weighted average of the filament plume impacts. The fluctuations due to meander are accounted for with a Gaussian distribution of the filament plume wind directions. Strimaitis et al. (1985) describe the form of the meander component.

Flow below H_c (WRAP)

The flow below H_c is considered steady and two-dimensional. Therefore, the flow must pass to one side of the hill or the other. The streamline which touches the hill, passes along the surface of both sides, and separates two flow regions

is the stagnation streamline (Fig. 3). Streamlines, on either side of the stagnation streamline, are deflected to the side but pass closer to the hill surface than their upstream separation (d) from the stagnation streamline. Adjacent streamlines are displaced by differing amounts and horizontal streamline spacing is altered. Thus, the local speed is changed. Fig. 3 shows a typical streamline pattern for flow around an elliptical terrain feature.

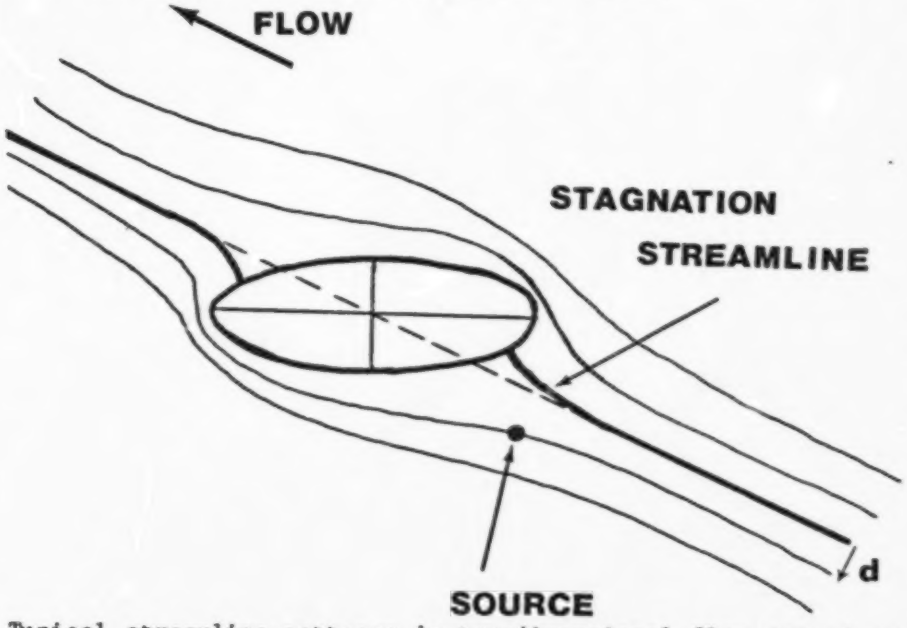

Fig. 3. Typical streamline patterns in two-dimensional flow around an elliptical cylinder. The distance from the stagnation streamline to the streamline which passes through the source is denoted as d. The x-axis is aligned with the mean upstream wind direction.

In simulating hill surface concentrations in flow around an ellipse, the WRAP formulation incorporates three key assumptions. (1) The lateral diffusion rate is assumed to be insensitive to deformation of the plume. Horizontal deformation of the plume (streamlines) is balanced by local flow speed changes so that material flux is unaltered. Streamline spacing can, however, alter diffusion rates (Hunt and Mulhearn, 1973), but observations from field studies associated with the EPA Complex Terrain Model Development program suggest that low-frequency turbulence controls crosswind plume growth over averaging periods of the order of

one hour. Therefore, alterations in diffusion rates caused by changes in streamline spacing are ignored by WRAP. (2) Vertical diffusion is assumed to increase with increases in travel time caused by flow alterations. Recent fluid modeling studies (Hunt, 1985) have shown the importance of increased travel time on the vertical growth of plumes. (3) The flow during the averaging period is assumed steady and all of the lateral variability, including meander, is considered as turbulence.

The formulation of the diffusion equation in WRAP is similar to that in LIFT with the primary difference arising from the location of solid boundaries and the relationship between those boundaries and wind direction. As in LIFT, the flow (plume) is re-initialized at s_o. In WRAP, s_o is the distance along the stagnation streamline to the terrain contour on which the receptor lies. At s_o and beyond, H_c separates the plume into two vertical layers and the stagnation streamline separates it into two horizontal segments. The concentration at a receptor is composed of contributions from that part of the plume at s_o which is below H_c and on the same side of the stagnation streamline as the receptor. Reflection is allowed, at any point, from the z=0 surface, and beyond s_o reflection is allowed from the hillside.

Assuming that the x-axis of the coordinate system is along the stagnation streamline and that the source is located at (x_r, y_r, z_r), the concentration at a hillside receptor at $(s,0,z_R)$ is given by

$$C(s,0,z_R;s_o) = \frac{Q}{4\pi u \sigma_y \sigma_z} e^{-0.5(\frac{d}{\sigma_y})^2} (1 + \text{sign}(y_R)\ \text{erf}(\frac{d\sigma_y^*}{\sqrt{2}\sigma_{yo}\sigma_y}))$$

$$\cdot (B_1 e^{-0.5(\frac{z_r - z_R}{\sigma_z})^2} + B_2 e^{-0.5(\frac{z_r + z_R}{\sigma_z})^2}) \qquad (4)$$

where d is the distance between the source streamline and the stagnation streamline (upstream from terrain effects), and sign (y_R) is +1 when the receptor is on the same side of the stagnation streamline as the source and -1 otherwise. The amount of plume spread over the distance from source to stagnation point (s_o) is denoted by σ_{zo} and σ_{yo}. The rate of plume growth from s_o to the receptor is denoted by σ_z^* and σ_y^*.

The factors B_1 and B_2 are given by

$$B_1 = \text{erf}\left(\frac{b_1-b_2-b_3}{b_o}\right) + \text{erf}\left(\frac{b_1+b_2+b_3}{b_o}\right)$$

$$B_2 = \text{erf}\left(\frac{b_1-b_2+b_3}{b_o}\right) + \text{erf}\left(\frac{b_1+b_2-b_3}{b_o}\right)$$

where

$b_o = \sqrt{2}\ \sigma_z\ \sigma_{zo}\ \sigma_z^*$

$b_1 = H_c\ \sigma_z^2$

$b_2 = z_r\ \sigma_{zo}^2$

$b_3 = z_r\ \sigma_z^{*2}$.

The primary effects of terrain on hill surface concentrations as modeled in Eq. 4 are (1) steering of the plume to the side modeled through the offset distance d, and (2) the increase in travel time modeled as an increase in vertical diffusion. Both the lateral offset and the time of travel are estimated from the theory of potential flow around an elliptical cylinder.

The diffusion parameter formulations (σ_z, σ_y)

The vertical plume spread parameter, σ_z, used in CTDM has the well-accepted form

$$\sigma_z = \sigma_w t/(1 + t/2T_{1z})^{1/2} \qquad (5)$$

where σ_w is the standard deviation of vertical velocity, t is the time of travel

and T_{lz} the Lagrangian time scale. T_{lz} is based on empirical flux-profile relationships of surface similarity theory and is given by Venkatram et al. (1984).

The lateral plume spread parameter, σ_y, takes a form similar to σ_z where

$$\sigma_y = \sigma_v t/(1 + t/2T_{ly})^{1/2} \qquad (6)$$

where σ_v is the standard deviation of the crosswind velocity. T_{ly} is not approximated from the flow properties but is estimated from the turbulence measurements as described by Strimaitis et al. (1985).

For buoyant releases, initial growth during plume rise is generally much greater than growth by ambient turbulence. Therefore, during the time of rise, the plume grows as if it experiences a greater time of travel. CTDM estimates a virtual time of travel to add to the travel time in Eqs. 5 and 6 to account for buoyancy-induced dispersion.

PRELIMINARY EVALUATION OF CTDM

The development of CTDM has been strongly supported by a series of four major field tracer studies and by a number of wind tunnel/towing tank experiments. Throughout the development period, the performance of progressively improved versions of CTDM has been examined with both the field and fluid modeling data bases. It is important to emphasize that development work is continuing on the model and that extensive testing, evaluation, and refinement of the model algorithms are forthcoming. The following is a discussion of some of the preliminary evaluations on the most recent version of CTDM.

Cinder Cone Butte tracer study

Tracer plume impingement studies were conducted during the fall of 1980 at Cinder Cone Butte (CCB), a roughly axisymmetric, isolated 100-m high hill near Boise, Idaho. The study, described in detail by Lavery et al. (1982) and

Strimaitis et al. (1983), produced a data base of over 100 hours of high-quality data suitable for dispersion model development and evaluation.

Reporting on a recent analysis, Lee (1986) discussed the ability of CTDM to identify maximum ground-level concentrations at CCB. The data set, for 80 tracer release hours, represented conditions of generally light to moderate wind speeds, very stable to near neutral stability, and tracer releases above and below the dividing streamline height. The release locations were generally about one kilometer from the center of the butte; the diameter of the near-circular base of CCB is about one kilometer.

Fig. 4 displays some results of Lee's analysis comparing highest observed one-hour concentrations on CCB with highest concentrations predicted by CTDM. Note that these comparisons are for estimates paired in time but not in space. As Fig. 4 indicates, CTDM is able to predict the highest surface level concentrations with some success (over 60% of the estimates are within a factor of two). However, for an isolated three-dimensional terrain feature such as CCB, estimates of the location of the maximum as well as the general concentration pattern on the butte have been found to be particularly sensitive to wind direction. For certain wind directions, a few-degree error in the direction provided to the model may cause an estimate of no plume impact when, in fact, a significant portion of the plume may be interacting with the terrain. This may partially explain the predicted concentrations near zero in Fig. 4, although observations clearly indicate plume-terrain interaction.

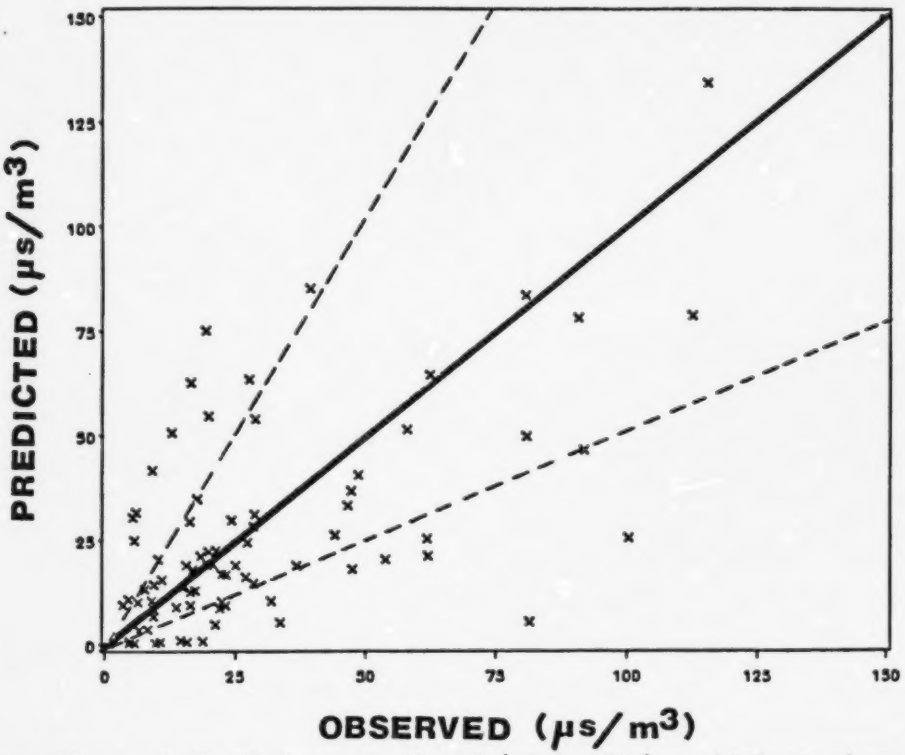

Fig. 4 Comparison of the highest predicted (with CTDM) to highest observed concentrations for 80 hourly averaging periods at Cinder Cone Butte. The concentrations are paired in time but not necessarily in space. The dashed lines are the factor-of-two lines. The units of $\mu s/m^3$ refer to concentrations normalized by emission rates.

The Full Scale Plume Study (FSPS)

The FSPS was conducted in August 1984 at the Tracy Power Plant, east of Reno, Nevada. The tracer gases were released from the 91-m stack to simulate a typical power plant release of pollutant. The plant is located in a long river valley with surrounding mountain peaks as high as 460 m above stack base. The FSPS data base is comprised of 128 hours with conditions ranging from very stable with light winds to morning inversion breakup and fumigation. Prolonged periods of stable conditions with westerly flow and frequent plume impingement on terrain east of the stack were common.

One significant terrain feature approximately 4.5 km east of the stack is Beacon Hill, rising about 300 m above stack base. Strimaitis et al. (1986)

discuss preliminary results of an analysis of 39 hours of the data base when the plume was advected to Beacon Hill. For these test hours, plume rise and initial plume size (after rise) were estimated by ground-based lidar measurements. The meteorological conditions were extracted from a 150-m tower located approximately one kilometer east of the stack (between the stack and Beacon Hill).

Fig. 5 shows the comparison of highest modeled (with the current CTDM model) to highest observed concentrations. As with Fig. 4, the concentrations are paired in time but not necessarily in space.

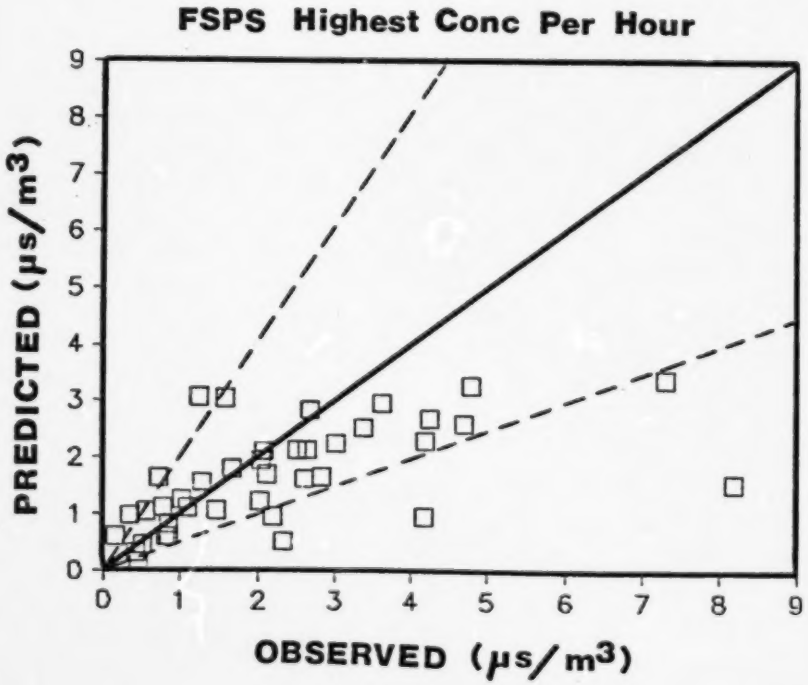

Fig. 5. Comparison of highest predicted (with CTDM) to highest observed concentrations for 39 hourly averaging periods at the Full Scale Plume Study. The concentrations are paired in time but not necessarily in space. The dashed lines are the factor-of-two lines. The units of $\mu s/m^3$ refer to concentrations normalized by emission rates.

Most of the cases where the normalized concentrations are less than $4\,\mu s/m^3$ the model predicts correctly within a factor of two (typically Gaussian). However, it notably underpredicts the higher observed concentrations (observed concentration $> 3\mu s/m^3$).

One reason for this tendency to underpredict pertains to the way that σ_z is estimated by CTDM in stable flows. The modeled σ_z (Eq. 5) is directly proportional to the fluctuations in the measured vertical velocity, σ_w. In stable conditions, σ_w from the measurements is the result of a mix of turbulence and wave motions. However, Eq. 5 assumes that σ_w results only from turbulence. Consequently, any wave motions would contribute to an overestimate of the true σ_z and an associated underestimate of centerline concentration. This effect is more important with large travel times (from source to receptor). For light winds ($\sim$1 m/s), the travel time to Beacon Hill exceeds an hour. DiCristofaro et al. (1986) discuss the model estimates of σ_z as compared with lidar and photographic estimates at FSPS.

Further detailed study of plume behavior in the FSPS data base will aid in the modification of CTDM such that overestimates of σ_z and other problems associated with long travel times can be more adequately addressed.

Fluid modeling observations

In work designed specifically to exercise the most recent version of CTDM, Snyder (1986) compared predictions by the model to laboratory fluid modeling observations of flow and diffusion over isolated hills. Included were wind tunnel simulations of neutral flow and towing tank simulations of stably-stratified flow with specific phases for investigating the overall performance of CTDM as well as the LIFT and WRAP portions individually.

In an overall test of CTDM, Snyder examined the flow around a model CCB hill during stable conditions. The plume was released very near to H_c so that both LIFT and WRAP were utilized. Snyder concludes that CTDM can reasonably predict the values of the highest concentration, however, the location of the maximum occurred at a slightly higher elevation in the tow tank than in CTDM. The concentration pattern was recognized well by the model with over 50% of the cases, paired in time and space, within a factor of two.

In additional tow-tank studies on three-dimensional hills, Snyder found that, above H_c, CTDM underestimates the lateral spread of the plume and overestimates the vertical deflection of the plume centerline. In other words, during stable conditions, CTDM predicts a plume that is too narrow laterally with a centerline too far from the hill surface. The fact that the model does not consider stratification (shear) in the flow above H_c is suspected as the reason for this behavior, and this is presently being investigated further. Similarly, in the neutral wind tunnel studies, the plume tended to stay closer to the hill surface than CTDM predicted.

SUMMARY

Preliminary evaluations of CTDM have shown that the model performs well in identifying maximum surface concentrations during stable conditions. However, several areas for model improvement have been identified.

For long travel times, the model tends to underpredict the higher concentrations. The effects of not excluding wave motions from the turbulence estimates used in the σ_z formulation are being studied as a possible reason for this underestimate.

Fluid modeling studies pointed out that in the LIFT domain, CTDM is not fully accounting for the lateral plume spread and the model is overestimating the

distance of the plume centerline from the surface. Introduction (into CTDM) of the effects of stratification (shear) in the flow above H_c is being investigated as a means of minimizing these discrepancies with the observations.

Further analysis of the extensive FSPS data base is expected to facilitate additional evaluations of CTDM and result in further improvements to the model formulations. Overall assessment of the accuracy, sensitivity and limitations of CTDM are forthcoming.

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